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Current facts about offshore wind farms

A. Madariaga[a,*,1], I. Martínez de Alegría[a,1], J.L. Martín[a,1], P. Eguía[a,2], S. Ceballos[b]

[a] University of the Basque Country (UPV/EHU), Engineering Faculty of Bilbao, Alameda Urquijo s/n, 48013 Bilbao, Spain
[b] Tecnalia Research & Innovation, Parque Tecnológico de Bizkaia, c/Geldo, Edificio 700, 48160 Derio, Spain

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ABSTRACT

This paper reviews offshore wind projects with a wide perspective. The current situation of the offshore wind market is presented, pointing out the countries leading the process in terms of installed capacity and in terms of technological leadership. Feasibility studies of alternative offshore wind farms (OWFs) are interesting not only in relation to the business but in relation to the techno-economical analyses that engineering researchers need to do. Details about the average energy yield assessment, the costs and the price for the purchased energy are commented on, as key elements of those feasibility studies. The higher cost of renewable energy sources of electricity (RESE) when compared with conventional sources, demands appropriate policy support. The European regulatory framework and the support schemes established by European Member States are presented, as well as the role that different transmission system operators (TSOs) are playing at the moment. Finally, most of the OWFs currently operating are presented, analysing the technical characteristics of their electric subsystems: the wind energy conversion systems (WECSs) transforming the kinetic energy of the wind into electricity, the collector system (CS) gathering the power output of all the turbines to a central collection point (CCP) and the transmission system (TS) taking that power to the onshore main grid.

Contents

* Corresponding author. Tel.: +34 946014191; fax: +34 946014200.
E-mail address: ander.madariaga@ehu.es (A. Madariaga).
[1] APERT Applied Electronics Research Team, http://det.bi.ehu.es/ apert/index_engl.html.
[2] GISEL Electric Power Systems Research Team. Department of Electrical Engineering.

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1. Introduction

The wind power capacity installed offshore worldwide during 2010 accounted for 1039 MW, exceeding the scenarios presented by the leading wind associations only two years before [1]. This meant a growth rate of about 49%, clearly above the increase in the onshore market for the same period, that was slightly over 30%. Although a similar growth rate was foreseen for the last year [2], the actual numbers have been lower than expected with a growth rate near 24%. Taking into account only OWFs commissioned and fully connected to the grid during the corresponding year, an analysis of the information collected from several wind farm databases [3,4] and of the main offshore wind farm operators' web pages (see Section 4) shows that the wind power capacity installed offshore worldwide during 2011 accounted for 715 MW. In the European Union (EU), 405 MW were connected last year, far from the almost 1 GW expected. Fig. 1 shows the evolution of offshore global wind capacity during the 2000–2011 period. In dark blue we see the installed capacity during the corresponding year, while each column height shows the cumulative offshore wind power installed worldwide.

However, this data does not show a slowing down in the offshore wind market growth rate. On the one hand, slight schedule delays in Ormonde and Walney-2 offshore wind power plants (OWPPs)[3] have postponed the commissioning and full connection to the European grid of nearly half the GW. On the other hand, the average output power of OWFs is continuously increasing [5], and this fact has a direct effect on installed capacity annual statistics, if we do not compute them until they are fully operational. For example, the 504 MW OWPP Greatter Gabbard, currently under construction off the Suffolk coast of the United Kingdom (SSE-RWE), started connecting offshore wind turbines (OWTs) to the grid early in 2011, but its commissioning is not expected until late 2012. Short term growth rate statistics could therefore appear distorted by this fact. This could be the reason why offshore wind statistics are being published in terms of installed OWTs and not in terms of OWFs fully connected to the grid [2,6].

The emerging offshore wind market has been led by the United Kingdom and Denmark during the first decade of this century. But the scale of the offshore wind business has changed and new actors have also decided to play a key role during this decade. On the one hand, German companies are showing their technological leadership providing integral solutions that take in most of the components needed in offshore wind projects. On the other hand, China undoubtedly has an enormous market potential and is fulfilling an ambitious renewable program [7,8]. Table 1 presents the offshore wind power capacity operating by the end of 2011 and a feasible projected scenario by the end of 2014, in which projects currently under construction will be already operating.

Regarding long term forecasts for the offshore wind industry, projections on installed capacity, investment and employment are regularly presented by the leading wind associations [2,9]. Investment and employment in the offshore wind power business are expected to grow considerably and continuously at least until 2030. However, other institutions are apparently less optimistic in their forecasts and that should oblige us to handle these projections carefully. For example, projections for the total wind power (onshore and offshore) installed in the EU by the end of 2020 are in a range between 199 GW and 230 GW, according to the projections published by the International Energy Agency and by European Wind Energy Association (EWEA), respectively.

[3] Throughout the paper, we use the term offshore wind farm (OWF) in a general sense, leaving the term offshore wind power plants (OWPP) for installations with a rated power above 150 MW.

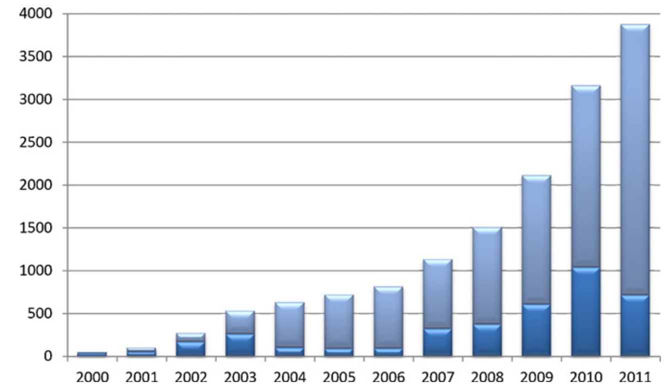

Fig. 1. Evolution of offshore wind power in MW (2000–2011).

Table 1
Foreseen offshore installed wind capacity by the end of 2014.

Country	December (2011) (MW)	Under construction (MW)	December 2014 (MW)
Belgium	195	296	491
China	446	1658[a]	2104
Denmark	863	400	1263
Finland	30	–	30
Germany	120	800	920
Ireland	25	–	25
Japan	24	–	24
Netherlands	247	–	247
Sweden	180	–	180
UK	1720	2759	4479
Total	3850	5913	9763

[a] Little information about Chinese OWFs is disclosed by developers and operators. That 1658 MW figure has been taken from the information disclosed in [4].

All in all, the offshore installed wind capacity is currently near 3.9 GW. A forecast of 9.8 GW installed worldwide by the end of 2014 seems realistic taking into account the projects already under construction. The countries that will lead this change of scale in the offshore business are the United Kingdom, Germany, China, Denmark and Sweden, some of them because they will principally undertake to install capacity and the others because they are demonstrating their technological leadership.

With that outlook in mind, the rest of the paper is organized as follows. Section 2 deals with feasibility studies of OWPP projects, with a subsection dedicated to each of the following aspects of these studies: the assessment of the average electric energy yield, the costs along the life-cycle of the power plant and the volatility that electric energy price shows in markets with a high degree of wind power integration. Section 3 focuses on the European regulatory framework and on the different support schemes proposed by Member States to promote the use of renewable energy sources of electricity (RESE). Section 4 deals with the technology used in OWFs installed by the end of the last year. The characteristics of the WECSs, CSs and TSs of those OWFs are commented on. Finally, Section 5 concludes summarizing the key aspects of the review.

2. Feasibility studies

The feasibility study of an OWPP is an analysis which by estimating the net energy production of the plant, a realistic price for the purchased energy and all the costs expected during the whole life-cycle of the installation, allows the potential investor to decide whether the investment is interesting just by deducting the costs from the incomes. Although the idea is quite simple, realistic and accurate economic feasibility studies for huge new projects like

OWPPs are an extremely difficult task. In the following subsections we present a review of the three key aspects of feasibility studies: production, costs and prices.

2.1. Average energy yield assessment

The electrical power output of a wind turbine is a non linear function of the wind speed, and it is usually disclosed by manufacturers in their platform data sheets. The power curve of the turbine being known, the assessment of the electric power production of an OWT is a matter of estimating the wind conditions at the site.

Although several different probability functions have been matched to observed wind speed distributions [10], the two-parameter Weibull probability density function is the most frequently applied for wind speed distributions over water surfaces [11]. The Rayleigh probability density function, a particular case of Weibull where the scale parameter is fixed to 2, can be used to estimate for how many hours a year the wind could blow in a certain speed range. The cumulative probability (CP) for a given wind speed (ω_s) can be determined by

$$CP = 1 - \exp\left[-\left(\frac{\omega_s}{c}\right)^2\right] \tag{1}$$

where the c parameter, which describes the sharpness of the distribution, can be calculated from the average wind speed at the site (v_a) by

$$c = \frac{2}{\sqrt{\pi}} \cdot v_a \tag{2}$$

For average energy yield assessment, the operating range of the turbine is usually *binnarized* in a certain number of steps, including a non-operating range for wind speeds above cut-out and below cut-in wind speeds [12]. Then, the number of hours that the wind speed blows in each of the considered speed ranges can be determined multiplying the number of operating hours in a year by the subtraction of the cumulative probabilities corresponding to the extreme wind speeds of the range [13]. Afterwards, the annual energy yield of the wind turbine in each operating range can be calculated multiplying the average power output in that range by the number of hours a year the turbine is expected to function in that speed range. Adding the energy yields in all the operating ranges we get the average energy yield on an annual basis.

Logically, the foreseen average wind speed at the site (v_a) is the key factor in the assessment of the wind conditions. Those projections should be based on measurements taken during a certain reference period and on the assumption of a stationary climate. Nevertheless, even with a stationary climate, inter-annual variability and seasonal fluctuations cause uncertainty in those projections. A long record of at least 30 years can be assumed to have an uncertainty of at least ±5%, whereas a reference period of one year has an uncertainty of at least ±15%. And the measurement infrastructure that those records demand can be rather costly. A rough estimation shows that a one year measuring campaign offshore will cost about EUR 100,000 [14,15]. Therefore, as in many other aspects of offshore wind, accurate feasibility studies for OWPPs have a higher cost than feasibility studies for onshore projects.

2.2. Life-cycle costs

The costs for the production of electricity in OWPPs can be widely classified into three categories: investment costs, operation & maintenance (O&M) costs and network connection costs.

- *Investment costs* are those that arise from the feasibility studies to the commissioning of the OWPP. They take in all the costs related to engineering, manufacturing, logistics, installation, legal consultancy, bank fees and interest during construction.
- *O&M costs* are those related to the *normal* operation of the OWPP during its whole operating life. The main cost centres are, on the one hand, the specialized staff and equipment these projects demand (helicopters, vessels, cranes, etc.) and, on the other hand, the cost of the energy not supplied under fault conditions or when turbines are out of their operating range.
- *Network connection costs* are those that the OWPP operator has to pay to the transmission system operator (TSO) or to the offshore transmission owner (OFTO) for the connection to an agreed interface point (IP), usually at the connection point substation (CPS). There are mainly two types of network connection costs:
  - Usually new high voltage assets are needed, although in some cases minor modifications in grid substations and lines can be enough.
  - As in onshore projects, balancing costs are those that arise from the power that TSOs need to have available for primary and secondary frequency regulation due to the intrinsic varying nature of the wind.

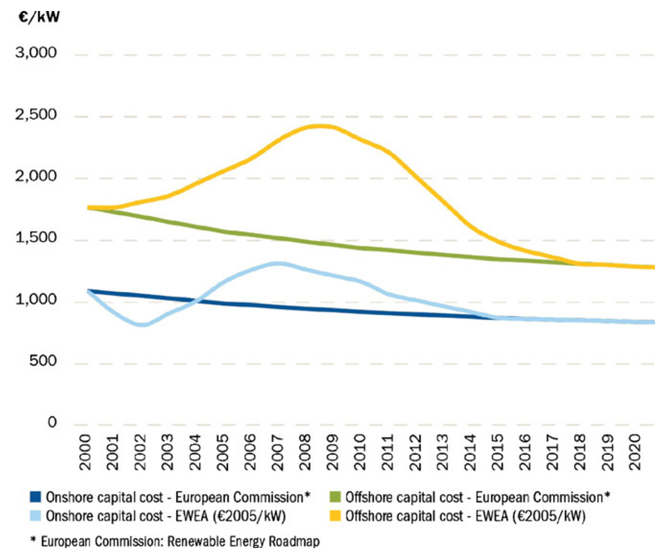

Fig. 2. Onshore and offshore wind capital cost (EWEA 2009) [1].

2.2.1. Cost data collected from first projects

According to the information reported from the first OWFs installed during the last decade, the costs of an OWF are considerably higher than for its onshore equivalent. Those costs increase significantly with the distance from shore, the sea bed depth and the distance from the main centres of demand. In order to get rough estimates of the cost of any OWF during preliminary stages, [16] suggests estimating first the cost for a baseline OWF placed in shallow waters very near the shore (Fig. 2) and then introducing the influence of water depth and distance from shore with a correction factor (Table 2). The distance between the OWF and the main centres of demand should also be considered, because the network connection costs could increase significantly in case of an OWPP placed far away from those demand centres.

Another interesting aspect is the breakdown of those costs and the identification of the main cost centres (Fig. 3). The main differences between offshore and onshore projects are the increase in logistics and O&M costs, as well as the higher investment costs in foundations and electrical infrastructure. This leads to a decrease in the project cost share of wind turbines from near 65% in onshore projects to about 30% in the offshore equivalents. A

Table 2
Cost factor dependency with distance and depth.

Depth (m)	Distance from shore (km)							
	>0	>10	>20	>30	>40	>50	>100	>200
10–20	1	1.02	1.04	1.07	1.09	1.18	1.41	1.60
20–30	1.07	1.09	1.11	1.14	1.16	1.26	1.50	1.71
30–40	1.24	1.26	1.29	1.32	1.34	1.46	1.74	1.98
40–50	1.40	1.43	1.46	1.49	1.52	1.65	1.97	2.23

detailed breakdown of the costs in offshore wind projects and up-to-date information about some of them can be found in [17].

Considering information about the first projects presented in [19], the average wind capacity cost is about 1995 EUR/kW, but data show a spread of values between the 1200 EUR/kW reported from the Middlegrunden project (2001) and the 2700 EUR/kW reported from the Robbin Rig project (2008). Regarding O&M costs, the variability of data coming from different projects and sources is also remarkable. Data reported by some of the early OWFs, awarded with capital grants by the British government and required to report on their performance for the first three years in turn, gave a range between 10 and 27 EUR/MWh, with most of the reported data between 12 and 24 EUR/MWh.

2.2.2. Current situation and projections

The current situation is characterized by higher capital costs than expected. The cost information reported from OWFs commissioned during the last years of the last decade slightly exceeds 3000 EUR/kW. This number goes clearly above the 2500 EUR/kW foreseen by several analysts for the same period [16,1]. Fig. 4 presents an up-to-date comparison between the costs of wind capacity installed onshore and offshore including data gathered from operating wind farms and EWEA's own projections.

Although it is clear that OWF capacity costs have increased above expected levels, a strong reduction is foreseen from here on. The offshore wind capital costs are expected to fall to about 1500 EUR/kW by 2020. The different actors involved in this subject are already pushing towards that objective. On the one hand, European States are forcing the offshore wind industry to decrease their costs by proposing lower energy price ceilings in the competitive tenders for offshore wind development zones. On the other hand, the component suppliers within the wind industry are trying to decrease their costs by building bigger turbines, by utilising similar parts for multiple turbines, by driving down the costs of their own suppliers and by increasing their global manufacturing footprint [20].

As we see, the different parts involved are already promoting policies and measures to achieve the objective, but it is not clear to what extent the goal will be fulfilled. On the one hand, as OWTs only account for about 30% of the total costs of offshore wind projects, the cost reduction for those components should be huge in order to have a substantial effect on total project costs. On the other hand, some analysts suggest that cost-decreasing effects of scaling and learning for offshore wind power can partly or entirely be offset by cost-increasing effects such as commodity price surges (aluminium, copper and steel) [21]. Therefore, capacity cost-reducing effects for offshore wind power could become apparent when copper and steel prices stabilize at their 2010 levels or return to their pre-2005 values (if that stabilization happens at all). As we see, forecasting the performance of a young industry is an extremely difficult task indeed.

2.3. Price volatility

The influence of big scale intermittent wind generation on the electricity market has been analysed in several recent papers. Some of them are based on the current situation, with most of the wind farms located onshore, and deal with detailed empirical analysis of the impact of renewable electricity support schemes on power prices in Spain, Germany, Denmark and Belgium [22–24].

Other studies also consider OWFs and analyse the influence that huge amounts of wind power can have on the electricity markets [25–27]. These studies show that average market remuneration for intermittent generation technologies are lower than for conventional generation. This is mainly due to the fact that when it is windy, smaller amounts of conventional generation technologies are required, and prices are lower, while at times of little wind, prices are higher.

Therefore, bearing in mind the high costs of OWPP projects and accepting the volatility that electricity markets show in the presence of large scale wind power, there would be little investment in offshore wind without specific and adequate policy support. Investors need a *power purchase agreement* that makes sure that they will be able to sell the electricity produced at a reasonable price

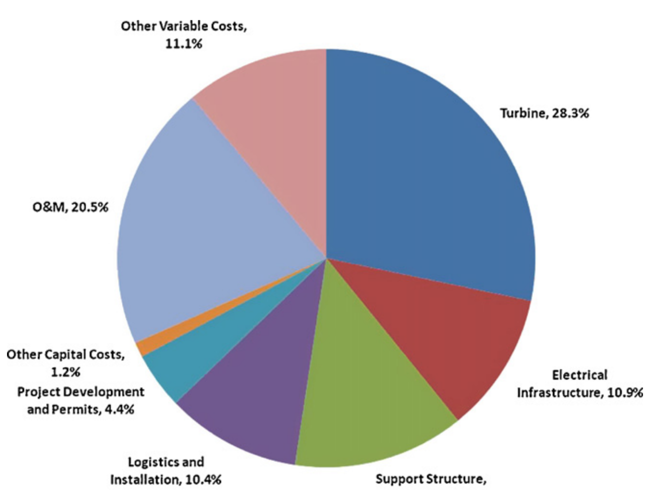

Fig. 3. Estimated life-cycle cost breakdown for a typical baseline OWF (NREL) [18].

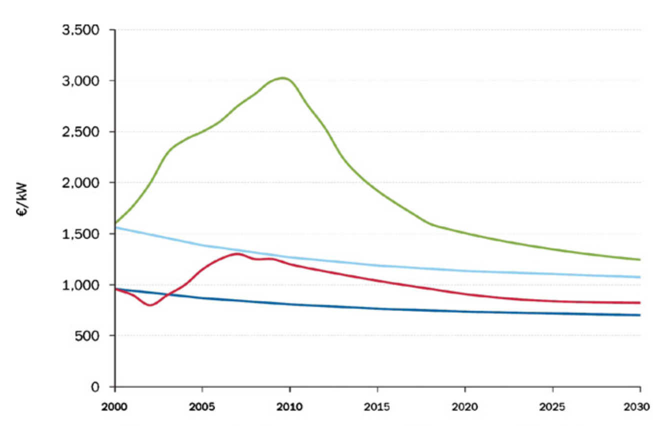

Fig. 4. Onshore and offshore wind capital cost (EWEA 2011) [2].

for at least 10 years. If there is no chance of paying back the investment between 10 and 15 years, the project will not be regarded as feasible and will therefore be discarded [14]. However, according to how the offshore market is behaving, the policies established by some of the EU Member States seem to be supporting enough.

3. European regulatory framework

3.1. Main references

The European Commission (EC) has increasingly supported legal instruments for ensuring fair play in the open electricity market and promoting the development and integration of RESE in Europe. The main instruments have been Directives adopted by the European Parliament and, in accordance with the principle of subsidiarity, Member States have been responsible for the transposition and application of those Directives. During 2009 two central Directives were approved by the European Parliament: 2009/28/EC and 2009/72/EC.

- 2009/28/EC [28]. This Directive establishes a common framework for the use of energy from renewable sources in order to limit greenhouse gas emissions and to promote cleaner transport. To this end, Member States have established their National Renewable Energy Action Plans (NREAPs) which define their own 2020 targets for the use of RESE, as well as the policies and measures to fulfill the established targets [29].
- 2009/72/EC [30]. This Directive is aimed at introducing common rules for the generation, transmission, distribution and supply of electricity. It also lays down universal service obligations and consumer rights, and clarifies competition requirements. In the light of the dysfunction in the internal market in electricity, it redefines rules and measures applying to that market in order to guarantee fair competition and appropriate consumer protection.

3.2. Support schemes

The promotion mechanisms for RESE can be based on one or more of the following: direct price support schemes, obligated quotas, investment aid and tax exemptions or reductions. Every EC Member State has already implemented its own strategy regarding RESE support. Currently, the support schemes used to promote offshore wind power are direct price support and obligated quotas.

- *Direct price support*. These schemes may appear in two different forms:
  - *Feed-in tariffs*. Utilities are obliged to buy electricity from any RESE generator at a previously fixed unit price, different for each technology.
  - *Premium*. Owners of renewable installations sell electricity on the open market (or through a freely negotiated price), supplemented by a specific premium for each renewable technology. This is the support scheme established in Spanish NREAP for OWPPs. Under this alternative, premiums vary on the basis of per-hour market prices:
    - In the event of low market prices floor price is guaranteed, meaning that the owner of a renewable installation can be assured a minimum return on the investment.
    - The scheme also establishes a ceiling premium payment, paying no premiums when market prices are high, thus helping to keep system costs as low as possible.
- *Obligated quota*. In this mechanism, suppliers or consumers are obliged by national law to provide a fixed percentage of renewable energy in the produced and/or consumed energy. Otherwise, penalties are applied. Most of the countries that have chosen this scheme have implemented *Tradable Green Certificatess (TGCs)* as a tool to implement this support strategy transparently. The TGCs are issued by a central authority to RESE generators, so certifying that a certain amount has been fed into the grid (e.g. one certificate per MWh of RESE). Then, generators sell TGCs to the obliged suppliers or consumers on an open market of renewable values (distinct from the market in actual electricity). Finally, TGCs are exchanged by the central authority, associating them with a given amount of RESE and taking them out of the market.

Among European countries Belgium, Italy, Sweden and the United Kingdom are supporting renewable energies by TGCs, while Denmark, France, Germany and the Netherlands are using feed-in tariffs. As mentioned before, Spain is taking a slightly different strategy for OWPPs, with a premium system. The premium for a kWh of offshore wind power sold in the Spanish electricity market has a reference value of cEUR 9.1041, and a ceiling for the market remuneration plus the premium of cEUR 17.7114. A detailed review of the current Spanish fixed feed-in tariff system can be found in [31]. For other European countries, economic values of the mentioned feed-in tariffs and TGCs support schemes can be found in [16].

3.3. Network connection costs

There are three different regulatory strategies to distribute network connection costs of wind farm projects: shallow, intermediate and deep charging systems [32].

- In a *shallow charging system* these costs are initially born by the TSO and afterwards *socialized* among all market participants.
- In a *deep charging system* the wind power producer contributes to the total grid reinforcement needed for a particular wind farm, which normally increases proportionally to the new capacity connected.
- An *intermediate charging system* tries to find an optimum balance between the previous two strategies.

The charging system adopted by the United Kingdom for the first OWFs could be considered intermediate, each wind farm's developer being responsible for connecting their station to shore, following the overall development plan, just as they are responsible for building the station itself [16]. But the control agency decided that this strategy falls foul of the 2009/72/EC Directive which tries to guarantee a high degree of separation between generation and transmission activities. Currently, the regulator runs tenders to appoint an OFTO for each wind development zone, which is responsible for building and operating the connection assets [33,34]. The Crown Estate, which is responsible for the economic use of the seas around the UK, has appointed a single lead developer for each of these zones, which allows for coordination between that developer and the OFTO for the zone [35]. OFTOs will also be appointed for the existing stations, paying their developers to take over the connection assets that they have built. But regarding the operation of those high voltage links, Great Britain's Security and Quality of Supply Standard [36][4] establishes clearly that they will be considered as a part of the National Electricity Transmission System.

Germany and Denmark have adopted a shallow charging system. Some researchers suggested that those schemes could prevent

[4] The standard follows the recommendations made by the offshore transmission expert group (OTEG), an expert group jointly organized by the Department of Trade and Industry (DTI) and the Office of Gas and Electricity Markets (Ofgem) of the United Kingdom [37,38]. A full set of definitions related to offshore wind can also be found in that standard. With no comment on the contrary, those definitions are used throughout the paper.

Fig. 5. HVDC links under construction for OWPPs (TenneT) [40].

efficient economic grid development of the whole system, because the evaluation of broader network extension planning is neglected, which if carried out would favour the best distribution of new wind generation into the grid [39]. However, this approach has helped to alleviate several uncertainties related to grid reinforcing and other system upgrade costs by sharing them between all market participants, who can equally benefit from the increased sustainable energy supply. It is remarkable that this strategy might have encouraged the German–Dutch TSO TenneT TSO GmbH to play a proactive role in the offshore wind business. Its affiliated company TenneT Offshore GmbH is the OFTO for the OWPPs approved and under construction in the German North Sea. Their ongoing projects to connect those wind farms with the onshore main grid through seven high voltage direct current (HVDC) links are especially interesting (Fig. 5)

4. Technology in OWFs

The components of OWFs can be classified into different systems depending on the aim of the analysis. In a study of the electric topologies for OWFs, we should consider as one entity all the components involved in wind energy conversion, in the collection of the power generated by all OWTs and in the transmission of that electric power to the onshore grid. It should be that way, even if those components are afterwards installed in different systems or even run by different operators. The following list classifies most of the components present in OWFs bearing in mind the above mentioned criteria.

- Foundations
- Turbines: tower, blades, shafts, WECSs
- WECSs
  - Gearboxes
  - Electrical generators
  - Electronic converters
  - Transformers
  - Cables
- CS
  - Medium voltage gas insulated switchgear (GIS) inside OWTs
  - Submarine collection cables
  - Medium voltage GIS at the offshore substation (OS) or at the CPS
- TS
  - OS
  - Submarine transmission cables
  - Landfall
  - Terrestrial transmission cables or/and overhead lines
  - CPS
- Other issues: control and protection system, installation and O&M equipment, staff, site.

Although in Section 2 we have seen that foundations are a key factor in the investment costs of offshore wind projects, they are not discussed in this section. A reader interested in foundations can find good surveys of all the technical alternatives currently under consideration in [18,41–43], details about foundations in operating OWFs in [44] and information about the leading floating concepts in the development stage in [45–50].

Following subsections deal with the technical characteristics of WECSs, CSs and TSs installed in those OWFs operating by the end of 2011. Tables 3 and 4 summarize the main facts of those OWFs [51–74]. OWPPs currently under construction/extension have also been considered to confirm the conclusions of the analysis and to detect technological trends [75–82].

4.1. Wind energy conversion systems (WECSs)

The size and rated power of wind turbines installed worldwide has increased continuously during the last decade. And this has been particularly true in the design of wind turbines for offshore applications, as bigger turbines in conjunction with enlarged load factors and more windy sites compensate investors for the higher costs of offshore projects. On principle, the type of WECSs installed in offshore wind farms are the same as those installed in the onshore equivalents, but adapted to the marine environment. However, considering electrical aspects, the main drawback of OWTs when compared to their equivalents onshore is the much higher costs of O&M operations. In order to minimize this drawback, the key issue is the generator type, the main alternatives being doubly fed induction generators (DFIGs), permanent magnet synchronous generators (PMSGs) and squirrel cage induction generators (SCIGs).

During the last decade, most wind turbine manufacturers have used a partially variable speed concept with a DFIG and a reduced power back-to-back converter connected to the rotor (Fig. 6(a)). With that scheme almost directly extrapolated to OWTs, the slip rings demand a rigorous preventive maintenance schedule, which is particularly costly offshore. Moreover, the only partial speed regulation of those turbines and the fixed grid frequency demands a complex and maintenance demanding gearbox. Another option is the use of a PMSG or SCIG in junction with full power IGBT based power converters (Fig. 6(b)). In both cases the slip rings and the corresponding maintenance operations are avoided. In addition, PMSGs can have a large number of poles, which slow down the turning speed of their rotor to values near those of the main shaft and, therefore, simplifies the gearbox or makes it unnecessary.

The following list summarizes the main advantages and drawbacks of each topology according to recently published reviews and analyses [84–87].

- The main advantages of DFIGs are considered to be low investment costs and high reliability, as it adapts technology widely used onshore to the new scenario. Its drawbacks are the rigorous and costly maintenance that slip rings and three-stage gearbox demand, as well as the limited rate of their wind speed control.
- The PMSG avoids the slip rings thus minimizing O&M requirements and helps in simplifying or even eliminating the gearbox due to its reduced rotating speed. The full power converter ensures maximum flexibility in the turbine response to voltage and frequency control, fault ride through and output adjustment.

Table 3
General facts of operating OWFs with rated power above 25 MW.

Name	State[a]	Year[b]	Operator[c]	Turbine	N_{wt}[d]	Power (MW)	D_{sb}[e] (m)	F_o[f]	D_{sh}[g] (km)
Huaneng Roncheng[h]	CH	2011	Huaneng	SL 3000/90	34	102	0–1	P	0
Walney 1 [51]	UK	2011	Dong-SSE	SWT-3.6-107	51	184	28	M	15
Baltic 1 [52]	G	2011	EnBW	SWT-2.3-93	21	48	19	M	16
Belwind 1 [53]	B	2011	Belwind	V90/3000	55	165	37	M	46
Chenjagang Xiangshui[h]	CH	2011	Yangtze	FD77-1.5	134	201	0–1	P	0
Thanet [54]	UK	2010	Vattenfall	V90/3000	100	300	25	M	12
Robin Rigg [55]	UK	2010	EON	V90/3000	60	180	9	M	10
Longyuan Rudong 1[h]	CH	2010	Guodian	SE 2.0	16	32	0–1	P	3.5
Rodsand 2 [55]	D	2010	EON	SWT-2.3-93	90	207	10	G	4
Donghai Bridge	CH	2010	SD	SL 3000/90	34	102	7	M	9
Gunfleet Sands [56]	UK	2010	Dong	SWT-3.6-107	48	173	15	M	7
Rhyl Flats [57]	UK	2009	RWE	SWT-3.6-107	25	90	11	M	8
Gäslingergrund [58]	SW	2009	VV	WWD-3-100	10	30	13	–	0
Alpha Ventus [59]	G	2009	DOTI	M5000-5M	6-6	60	33	T-J4	45
Horns Rev 2 [60]	D	2009	Dong	SWT-2.3-93	91	209	17	M	27
Thorntonbank I [61]	B	2009	CP	5M	6	30	19	G	29
Lynn-Inner Dowsing [62]	UK	2009	Centrica	SWT-3.6-107	54	194	11	M	5
Kemi Ajos [63]	F	2008	PV	WWD-3-100	10	30	7	–	0
Prinses Amalia [64]	N	2008	Eneco	V80/2000	60	120	24	M	23
Egmond aan Zee [65]	N	2008	V-NZW	V90/3000	36	108	18	M	10
Lillgrund [66]	SW	2007	Vattenfall	SWT-2.3-93	48	110	9	G	7
Burbo Bank [67]	UK	2007	Dong	SWT-3.6-107	25	90	8	M	7
Barrow [68]	UK	2006	Centrica	V90/3000	30	90	20	M	8
Kentish Flats [69]	UK	2005	Vattenfall	V90/3000	30	90	5	M	10
Scroby Sands [70]	UK	2004	EON	V80/2000	30	60	15	M	3
Arklow Bank 1 [71]	IR	2004	SSE	GE 3.6 Off	7	25	25	M	10
Rodsand 1 (Nysted) [70]	D	2004	D-EON	SWT-2.3-82	72	166	10	G	10
North Hoyle [72]	UK	2003	RWE	V80/2000	30	60	12	M	8
Horns Rev [73]	D	2002	V-D	V80/2000	80	160	14	M	14
Middlegrunden [74]	D	2001	D-MWTC	B76/2000	20	40	6	G	2

[a] B for Belgium, CH for China, D for Denmark, F for Finland, G for Germany, IR for Ireland, N for the Netherlands, SW for Sweden and UK stands for the United Kingdom.
[b] Year in which the OWF was commissioned and fully connected to the grid.
[c] CP stands for C-Power, DOTI for Deutsche Offshore-Testfeld und Infrastruktur GmbH, D for Dong Energy, EnBW for Energie Baden-Württemberg AG, MWTC for Middlegrunden Wind Turbine Cooperative, NZW for Nordzeewind, PV for Pohjolan Voima, RWE for RWE Npower Renewables, SSE stands for Scottish and Southern Energy, SD stands for Shanghai Donghai Wind Power Generation Company Ltd., V for Vattenfall and VV for Vindpark Vänern.
[d] Number of wind turbines in the OWF.
[e] Maximum water depth to the lowest astronomical tide within the OWF area.
[f] Foundation type, where *P* stands for high-rise pile cap foundations, *G* stands for gravity based foundations, *M* for monopiles, *T* for tripods and *J4* for four legged jacket.
[g] Distance to the nearest shore, which does not necessarily correspond to the length of the submarine cable.
[h] Chinese OWPPs projects do not have dedicated web pages as is usual in Europe. We have also been unable to find any information disclosed by operators of those OWPPs and the information presented has been retrieved from [4]. Moreover, those installations seem to be in intertidal areas, only partially covered at high tides, so it is not clear if they should be more appropriately classified as near-shore wind farms.

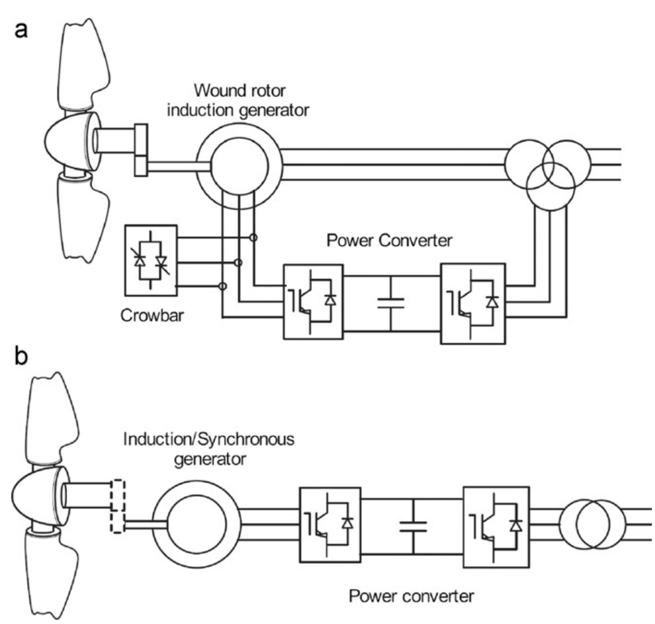

Fig. 6. WECSs in already operating offshore wind farms. (a) DFIG for partially variable speed operation [83]. (b) PMSG and SCIG for variable speed operation [84].

Direct driven configurations are an attractive choice with this type of generator, because of gearbox elimination and cost reduction due to small pole-pitch design.

- The SCIG minimizes O&M requirements and the full power converter ensures maximum flexibility in the turbine response with characteristics similar to those previously commented on. Its main drawback is that a maintenance demanding three-stage gearbox is needed and that direct drive configurations are not feasible with this type of generator.

Regarding WECSs used in already operating OWFs, about half of them are based on DFIG topologies, whereas the other half is based on SCIGs and full power converters (Table 5). It is also remarkable that about 80% of the turbines installed during last year in European seas were based on a SCIG solution, which shows a clear trend to instal full power electronic converters in offshore WECSs.

The electrical losses inside these WECSs are also a relevant issue and, apart from the generator type, another issues under consideration are the locations of the electronic converter and the power transformer inside the OWT. We see different strategies in the following three examples. In the SWT-2.3-93 the generator is located in the nacelle and the frequency converter and 0.69/33 kV transformer are located at the base of the turbine tower. In the SWT-3.6-107 the full power converter has the rectifier installed in the nacelle and the inverter in the tower base, both of them

Table 4
Collector and transmission network characteristics of operating OWFs with rated power above 25 MW.

Name	CS				OS	TS			
	N_{clu}[a]	V_{cs}[b] (kV)	D_{wt}[c]	L_{cs}[d] (km)		V_{ts}[b] (kV)	N_{cab}[e]	L_{lf}[f] (km)	L_{cpss}[f] (km)
Huaneng Roncheng	–	–	–	–	–	–	–	–	–
Walney 1 [51]	5	33	–	–	1	132	1	45	1
Baltic 1 [52]	–	33	–	–	1	150	–	61	–
Belwind 1 [53]	6	33	5.6–7.2	50	1	150	1	52	3
Chenjagang Xiangshui	–	–	–	–	–	–	–	–	–
Thanet [54]	10	33	5.6–8.8	55	1	132	2	26	3
Robin Rigg [55]	–	–	–	–	2	–	–	–	–
Longyuan Rudong 1	–	–	–	–	–	–	–	–	–
Rodsand 2 [55]	–	33	–	–	1	132	–	–	–
Donghai Bridge	–	–	–	–	–	–	–	–	–
Gunfleet Sands [56]	–	33	–	–	1	132	–	8.5	–[g]
Rhyl Flats [57]	3	33	–	–	0[h]	33	3	–	2
Gäslingergrund [58]	1	20	–	–	–	–	–	–	–
Alpha Ventus [59]	2	33	6.6	16	1	110	1	61	5
Horns Rev 2 [60]	7	–	–	70	1[i]	–	–	–	–
Thorntonbank I [61]	1	36	7.0	50.8	1[j]	150	2	36	3.3
Lynn-Inner Dowsing [62]	6	36	–	32	0[j]	36	6	40	–
Kemi Ajos [63]	–	–	–	–	–	110	–	0	–
Prinses Amalia [64]	10	22	–	45	1	150	1	28	7[g]
Egmond aan Zee [65]	3	34	–	–	0	34	3	–	7
Lillgrund [66]	5	33	–	22	1	130	1	7	2
Burbo Bank [67]	3	33	5.0–6.7	5	0	33	3	8	3.5
Barrow [68]	4	33	5.6–8.3	–	1	132	–	27	3
Kentish Flats [69]	3	33	7.8–7.8	18.9	0	33	3	10	2.6
Scroby Sands [70]	–	–	–	–	0	–	–	–	–
Arklow Bank 1 [71]	–	–	–	–	–	–	–	–	–
Rodsand 1 (Nysted) [70]	8	33	5.9–10.4	48	1	132	–	11	18
North Hoyle [72]	2	–	–	16	0	–	2	22	–
Horns Rev [73]	5	33	7.0	–	1	150	1	21	–
Middlegrunden [74]	1	30	2.4	3.5	0	30	2	2	1.5

[a] Number of clusters of turbines according to their electrical arrangement, not to their geometrical disposition.
[b] V_{cs} and V_{ts} stand for the voltages of the CS (also known as *internal grid*) and the TS, respectively.
[c] Separation among the turbines factorized by the turbine diameter. When two values are given, they account for the geometrical distances between turbines in a row and between rows, respectively.
[d] Total length of the MVAC collector system of the farm.
[e] Number of cables for the TS. Three phase high voltage alternating current (HVAC) submarine cable with optic fibre for communications is the general case.
[f] The length of the TS is the length of the submarine cable (L_{lf}), in most cases between the OS and the landfall, plus the length of the onshore transmission line (L_{cpss}), between the landfall and the CPS.
[g] A three phase submarine cable is connected in the landfall to three single phase and communication cables.
[h] Data corresponding to ongoing second and third phases of Thorntonbank OWPP.
[i] It is the first OS to offer accommodation facilities for O&M staff and visitors.
[j] When there is no OS, each cluster of OWTs has its own transmission cable, at least as far as the landfall, the voltages of the collection and transmission systems being the same.

Table 5
Wind turbines already operating in commissioned OWFs.

Manufacturer	Model	Years	Rated power (MW)	Generator	Gearbox	Total installed (MW)	Quota (%)
Repower	5M	2009	5.0	DFIG	3	60	2.0
Areva	M5000	2009	5.0	PMSG	2	30	1.0
Siemens	SWT-3.6-107	2007–2011	3.6	SCIG	3	731	23.5
Vestas	V90/3.0-Off	2006–2011	3.0	DFIG	3	933	29.2
Sinovel	SL 3000/90	2010–2011	3.0	DFIG	3	204	6.6
Winwind	WWD-3-100	2008–2009	3.0	PMSG	0	30	1.0
Siemens	SWT-2.3-82/93	2004–2011	2.3	SCIG	3	740	23.7
Vestas	V80/2000	2002–2008	2.0	DFIG	3	400	12.9

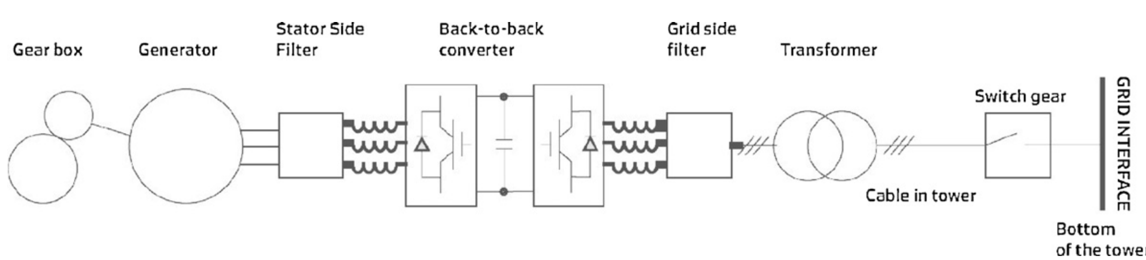

Fig. 7. V112/3.0-Offshore WECS (Vestas).

coupled by a DC bus responsible for taking the electric power down the tower. In the V112/3.0-Offshore (Fig. 7) the full power back-to-back converter and the power transformer are placed up in the nacelle, and the electric power is taken down at 33 kV minimizing the electric power lost inside the turbine [13].

Considering the offshore platforms with rated power between 3.0 MW and 7.0 MW presented during the last year, our analysis shows only one clear trend, which is to use PMSGs in all those WECSs with full power electronic conversion. However, different solutions are proposed also for PMSG based offshore wind turbines. Some manufacturers are proposing direct drive topologies based on PMSGs for OWTs in the range between 3.0 MW and 6.0 MW (Alstom, Nordex, Siemens, XMEC-Darwind, General Electric, and WinWind). Other manufacturers are proposing solutions based on PMSGs with simplified gearboxes in the range between 5.0 MW and 7.0 MW (Areva, Gamesa and Vestas). And turbines based on DFIGs are also a feasible option in the 3.0–6.2 MW range (Bard, Repower, Sinovel and Vestas). Therefore, the debate about which is the best WECS topology for offshore wind turbines could be out of date. It could be more interesting to focus on how to choose the technically feasible WECS that better suit an offshore wind project.

4.2. Collector systems (CSs)

The purpose of the CS (also known as *internal grid*) is to collect the electric power output of all the turbines and bring it to a CCP, which then ties in to the main grid. Its limits are usually the medium voltage GISs placed at tower bases and the medium voltage GISs placed at the OS or at the CPS. There are two main general configurations for CSs:

- When an OS is installed to adapt the voltage level to that of the TS, the collector system ends at the medium voltage GISs placed at the offshore substation. About 80% of the installed capacity follows this general layout (*big AC windparks* according to [88]).
- When no OS is installed (*small AC windparks* according to [88]), the CS ends at the medium voltage switchgears at the CPS and there is not a clearly defined TS. In these OWFs, one turbine in each cluster is connected to the onshore CPS with the same type of cable used to interconnect the turbines (at voltages near 33 kV). Therefore, there are as many transmission cables as clusters of turbines. This layout has been used in about 20% of the installed capacity (always very near to the shore) but none of the OWPPs currently under construction follow this general layout.

With slight differences depending on the foundation type and on the seabed characteristics, all the CSs reviewed follow a similar pattern in the interconnection of turbines to the CCP. According to electrical criteria, the OWTs are organized in clusters that group between five and 10 of them depending on the ratings of turbines and submarine cable (Fig. 8(a)). The most cost-effective CS nowadays seems to be the string cluster type with a voltage near 33 kV. This CS design is also know as radial collector system [89]. However some of the OWPPs currently under construction have shifted to a double sided ring CS design, probably in an attempt to maximize the power export availability keeping the investment cost as low as possible.

The connections of the turbines to the CS are made through medium voltage GIS placed inside the turbines and sited at the tower bases [91]. The connection between those medium voltage (MV) switchgears sited in adjacent turbines is made by application specific medium voltage alternating current (MVAC) submarine cable, most of the times buried 1–2 m into the seabed (Fig. 8(b) and (c)). The distances between turbines in an OWPP have to be carefully chosen to minimize the power loss because of the wake effect. As a general rule, this distance is taken to be about 7 times the rotor diameter. The data collected confirm this value and show two slight tendencies: an increase in that value with the increase in the rated power of the OWT and a decrease in that value with an increase in the mean wind speed on the site.

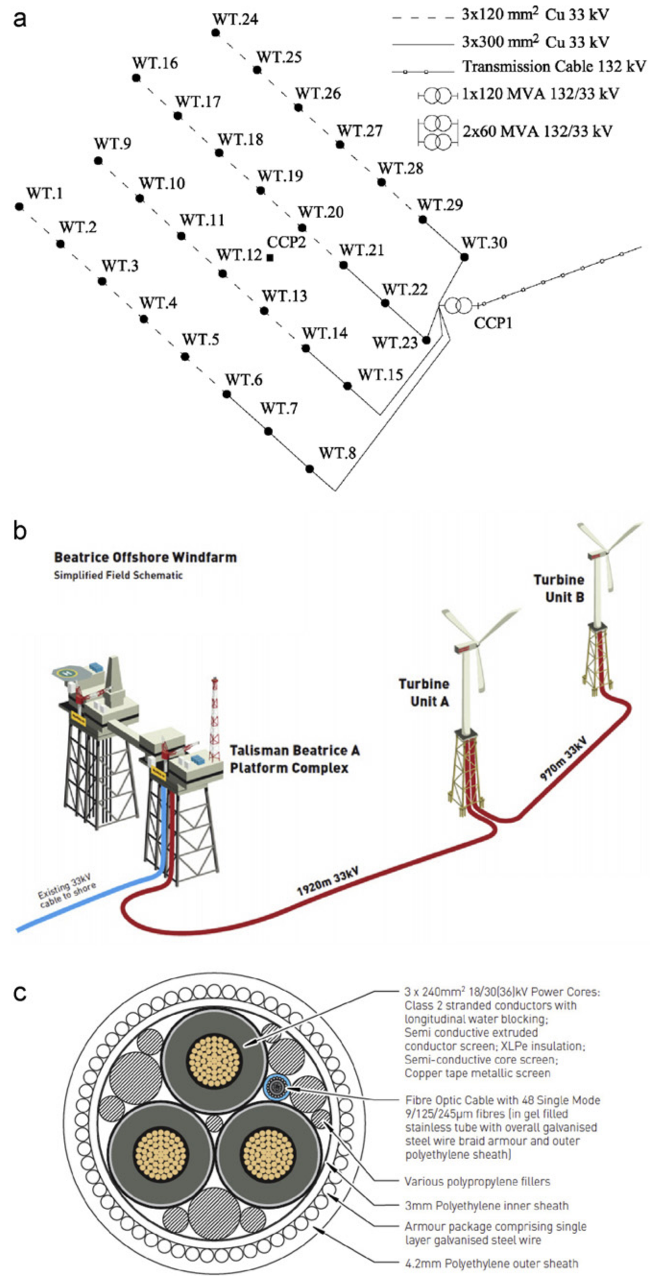

Fig. 8. Examples of CS layout and components. (a) Barrow OWF's collector system (Centrica) [90]. (b) Beatrice OWF demonstration project (Talisman). (c) GGabbard 33 kV submarine cable slice (JCR cable).

4.3. Transmission systems (TSs)

The TS is responsible for taking the electric power collected from the turbines to the onshore main grid. According to [36], the functional parts of an offshore TS may include the following:

- Offshore connection facilities on the offshore platform (OS) with:
  - one or more offshore (GEPs) at which OWPPs feed into the offshore TS,

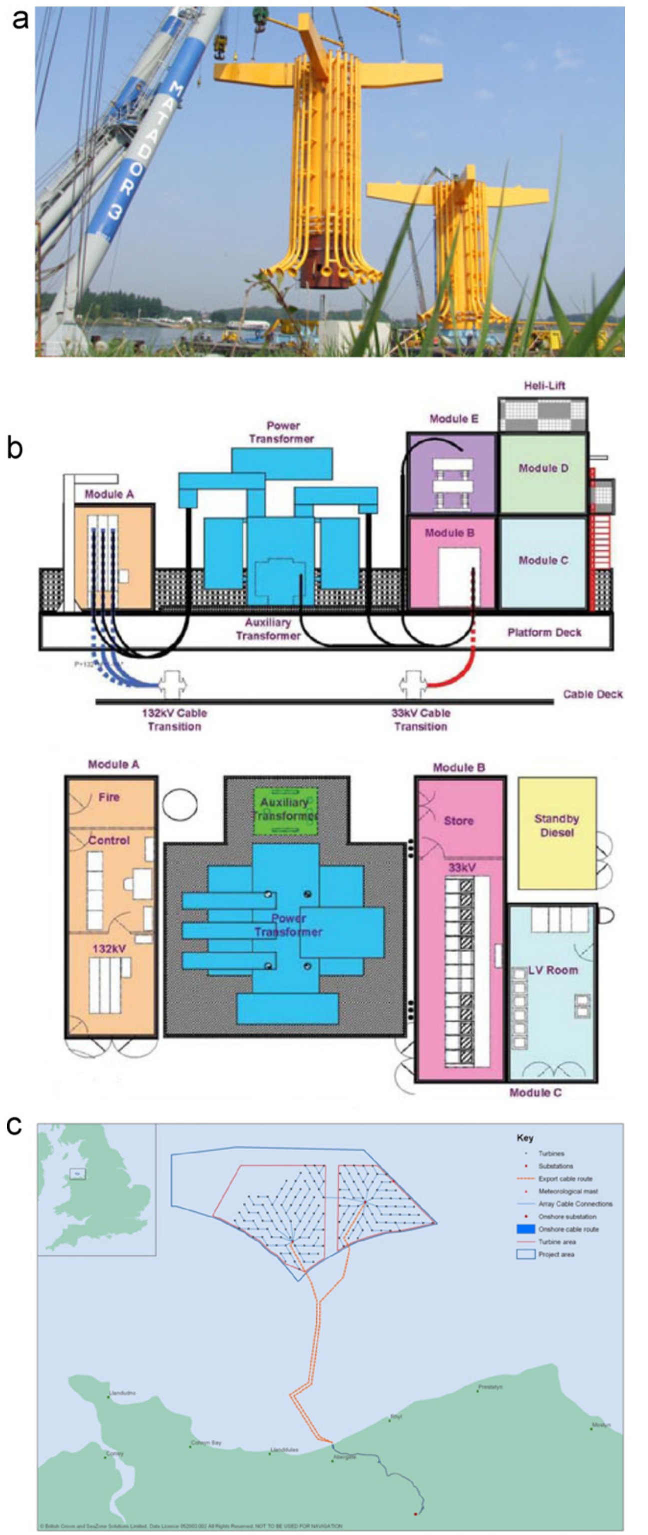

Fig. 9. OWPP transmission system components. (a) OS transition piece at London Array (Windpower Monthly). (b) Examples of OS layout elevation plans [92]. (c) Gwynt and Môr transmission system plan (RWE).

– one or more offshore supply points (OSPs) where OWPPs' electric energy demand is supplied from the offshore TS,
– transmission circuits in Alternating Current (AC) or Direct Current (DC).

- AC or DC cable offshore transmission circuits.
- AC or DC overhead line offshore transmission circuits.
- Onshore connection facilities, with AC or AC/DC conversion facilities connecting AC or DC cable or overhead line offshore transmission circuits to the interface point (IP). Such facilities may constitute the first onshore substation (CPS).

Considering these definitions, the scope of the offshore TS extends from the offshore GEP to the onshore GEP, also known as IP. These boundary GEPs are usually placed in the OSs and in the CPSs. The default point of connection is taken to be the busbar clamp in the case of an air insulated substation, or the gas zone separator in the case of a GIS substation. This is a major issue as those electric components delimit the responsibilities of the different partners involved in OWPP projects.

Most of the OWFs reviewed have installed HVAC submarine cable, at voltages between 110 and 150 kV. In those cases, a MVAC submarine cable goes from each of the clusters to the bottom of the OS, where they are pulled up and collected in a bar (Fig. 9(a) and (b)). Then, a power transformer raises the voltage level to that of the transmission cable (Fig. 9(b)). The small and medium sized OWFs installed until 2008 use just one cable for the transmission. On the contrary, bigger OWPPs usually have more than one transmission cable to take the generated power to the onshore grid (Fig. 9(c)). For example, *Thanet* OWPP with a rated power of 300 MW and commissioned in 2010, has two 3 phase HVAC cables for the transmission [54]. This trend is confirmed by huge OWPPs under construction like *Greater Gabbard*, with an expected rated power of 504 MW, two 33/132 kV OSs and three 3 phase HVAC cables for the transmission [76,77]; or *London Array*, with an expected rated power of 630 MW, two 33/150 kV OSs and four 3 phase HVAC cables for the transmission of the generated power to the CPS [79].

5. Conclusions

Taking into account the OWFs fully commissioned, the wind power capacity installed offshore during the last year accounted for about 715 MW, leaving the global offshore installed wind capacity near 3.9 GW. The countries that are leading the change in scale of the offshore business are the United Kingdom, Germany, China, Denmark and Sweden in terms of installed capacity and technological leadership.

A procedure to assess the average yield of an OWT is presented. Its inputs are the power curve of the OWT and the mean wind speed at the site. Regarding the costs of offshore wind projects, data of the overall costs of the first OWFs are gathered, as well as their breakdown in the main cost centres. The current situation is characterized by higher capital costs than expected, with an average near 3000 EUR/kW. However, although all the parts involved in the offshore wind business are determined to push down those costs to about 1500 EUR/kW by 2020, it is not clear to what extent that ambitious goal will be achieved.

Considering those high costs and the volatility that electricity markets show in the presence of bulk wind power, investment in offshore wind demands specific and adequate policy support. The European regulatory framework and the support policies adopted by European Member States through their NREAPs have been presented. As the amount of wind power in European grids increases, the role of TSOs in offshore wind power integration is essential. The different approaches in the United Kingdom and Germany are presented and recently published standards and key ongoing projects are commented on.

The current situation of all the OWFs with a rated power above 25 MW has been studied and the main characteristics in their WECSs, CSs and TSs have been summarized in the last section of the article. We conclude that although there is a long way to go until optimized solutions are available in the offshore wind business,

leading manufacturers offer products already tested which can be considered almost industrialized under certain conditions of sea bed depth and distance from shore.

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